10. The Unique Nature of the Davis-Besse Nozzle 3 Crack and the RPV Head Wastage Cavity

In the context of the nuclear industry, the cracks in Davis-Besse Nozzle 3 and its associated J-groove weld, and the unprecedented RPV head wastage that they caused, were not the result of ordinary “wear and tear.” This unique combination of circumstances represented an unexpected, unforeseeable, and extraordinary event of the moment. It occurred in the October/November 2001 time period when the leakage rate increased rapidly from 0.02 gpm from the nozzle crack alone, to approximately 0.16 gpm (84,000 gallons per year). This rapid, eightfold increase in RCS leak rate was the result of the uncovering of the large, 0.7-inch-long J-groove weld crack near the same location as the nozzle crack. In turn, this created a unique thermal hydraulic environment in the wastage cavity that resulted in metal removal and cavity growth at not just an unusual, but at an unprecedented rate.

The Davis-Besse Nozzle 3 Crack 1 remains the longest axial CRDM nozzle crack ever found, over twice the length of any CRDM axial nozzle crack reported in ERPI MRP-110, and it grew at a rate four times greater than any previously observed CRDM nozzle crack. The wide radial/axial weld crack at CRDM Nozzle 3, in line with the axial crack and the wastage cavity at the 10° location, was the only weld crack reported to have been exposed by RPV head cavity wastage.

Our crack growth, CFD modeling, and analysis of the potential metal removal and wastage mechanisms lead us to conclude that the downward growth of the wastage cavity accelerated after the axial nozzle crack intersected the wastage cavity shortly before October/November 2001. At this point, there was only around 1 inch of RPV head steel remaining between the bottom of the wastage cavity and the upper surface of the stainless steel cladding. The aggressive metal removal processes in the bottom of the cavity would have removed this remaining metal in a relatively short period of time, as little as a few weeks.

The metal removal process significantly accelerated again after the downward growing wastage cavity reached the RPV stainless steel cladding, the large pre-existing weld crack was uncovered, and the leak rate increased by an order of magnitude. This sequence of events leads us to conclude that most of the wastage cavity formation occurred, from October/November 2001 through February 2002.

We further conclude that at 12RFO in April-May 2000, any incipient sub-surface wastage cavity at Nozzle 3 would have been insignificant in size and extent, and much smaller than the wastage cavity eventually found at Nozzle 2 in February 2002. It would not have been visible at 12RFO, even if the RPV head had been completely cleaned of boric acid deposits during the outage. Moreover, even had there been no pre-existing boric acid deposits on the RPV head from CRDM flange leakage at 12RFO, the sub-surface cavity that was present would not have been detectable from the very small enlargement of the nozzle annulus that may have been present at that time.

10.1 Wastage Cavities at Nozzles 3 and 2

10.1.1 Physical Appearance and Characteristics of the Wastage Cavity at Nozzle 3

The detailed physical examination of the large wastage cavity at CRDM Nozzle 3 after a portion of the RPV steel containing the cavity was removed from the RPV head and examined in the laboratory[1] shows the following principal characteristics (Figures 10-1 through 10-4):

- The cavity extends down to the upper surface of the stainless steel cladding, exposing both the cladding and the J-groove weld.
- The cavity extends approximately 8 inches towards nozzle 11, is a maximum of approximately 4 inches in lateral dimension, and extends back to approximately the 90° and 270° points on the nozzle bore.
- The total volume of alloy steel removed was approximately 195 cubic inches.

- The cavity is centered on the large axial/radial crack in the J-groove weld at CRDM Nozzle 3 at the 10º location.

- The axial Crack 1 in Nozzle 3, which extended 1.23 inch above the top of the J-groove weld, is also approximately centered on the wastage cavity.

- The cavity morphology is indicative of a combination of processes, including mechanical removal by impingement of high velocity fluid, flow assisted corrosion, and boric acid corrosion.

- The corrosion process is clearly more dominant in the upper region of the cavity. There is clear evidence of mechanical removal and/or flow-assisted corrosion in the lower region, where the wastage cavity is clearly undercut. This lower undercut region is indicative off a more rapid metal removal process than at the mid-elevation point of the cavity.

- General corrosion of the upper RPV head surface around the cavity is evident to a depth of 1 to 1.5 inches. This can be seen in the view of the top section of the cavity (Figure 10.4) and more clearly shown in the dental mold impressions (Figure 10.5).

10.1.2 Physical Appearance and Characteristics of the Wastage Cavity at Nozzle 2

Field examination of the much smaller wastage cavity at CRDM Nozzle 2 by means of a borescope camera revealed the following characteristics (Figures 10-6, 10-7):

- The wastage cavity was located above three of the through wall axial cracks in Nozzle 2, in the upper half of the nozzle bore, centered on the 270° location.

- The wastage area was located 180º away from the two longest axial cracks in Nozzle 2, which were either side of the 90º location.

- Enlargement of the annulus clearance at the upper surface of the RPV head was observed at approximately the 90° location.
- None of the axial cracks extended up into the wastage cavity.
- The wastage area extended approximately 3 ½ to 4 inches down from the upper surface of the RPV head and was 50° (1 ¾ inches) in circumferential extent.
- The maximum penetration of the cavity into the RPV head was approximately 3/8 inch in the radial direction away from the nozzle OD, and this maximum point was approximately 1 ¾ inches below the upper surface of the RPV head. This indicates that whatever processes of mechanical removal, corrosion, or flow-assisted corrosion were active; the cavity was growing at its maximum rate sub-surface.

10.1.3 Cracks in CRDM Alloy 600 Nozzle 3 and Alloy 182 Weld

The inspection data derived from the extensive UT examination of CRDM Nozzle 3 before the wastage cavity was discovered, as well as the later definition of the crack profile from the UT data, provide significant information about the long through-wall Crack 1 in CRDM Nozzle 3. Unfortunately, this crack was completely destroyed when the lower part of the nozzle was bored out for repair.

However, careful metallurgical examination of the portion of the J-groove weld that remained after the RPV head section containing the cavity was removed from the RPV head, together with the UT data, allowed us to build up a composite picture of the large nozzle and weld crack at CRDM Nozzle 3 that is shown in Figure 10.8 (See Section 8.4.2).

The large cracks at Nozzle 3 show the following characteristics (Figures 10-9 through 10-14):

- A large axial through-wall crack (Crack 1) at the 3° location at the top of the J-groove weld extended from almost the bottom of Nozzle 3 to 1.23 inches above the weld on the OD.

- This axial nozzle crack appears to have extended into and almost completely across the J-groove weld at Nozzle 3.

- The metallurgical examination of this weld crack showed that it was quite wide and extended approximately 0.75 inches across the weld in the radial direction at the 10º location (Figures 10.9 through 10.14).

- The weld crack was in line with the upward bulge and crack in the stainless steel cladding at the bottom of the wastage cavity. The bulge in the cladding may have contributed to opening of the weld crack.

The fact that the weld crack and to a lesser extent the nozzle crack at Nozzle 3 are in line with the centerline and "nose" of the wastage cavity at approximately the 10º location indicate that they are manifestations of the same crack. This crack, more likely than not, initiated on the nozzle OD below the weld, and then propagated axially up through the nozzle wall around the weld, radially towards the ID eventually reaching through-wall, and radially out through the weld. The possibility of multiple initiation sites on both the OD and ID of the nozzle cannot be ruled out, and this would have shortened the overall time for the crack to reach the top of the weld and begin leaking (see Section 8.1.1).

This process of crack growth resulted in the long axial crack that leaked initially from the nozzle into the annulus and wastage cavity, and later through the weld crack directly into the wastage cavity.

10.1.4 Metal Removal Processes by Corrosion, Erosion, Flow Assisted Corrosion (FAC), and Water Jet Cutting (WJC)

Data from extensive boric acid corrosion testing prior to 2002 shows that corrosion rates in concentrated aerated aqueous boric acid corrosion can be as high as 8 inches per year, and metal penetration rates due to jet impingement can be up to 11 inches per year (Section 6.3).

Recent data from EPRI (Section 6.4.1) and NRC/ANL (Section 6.4.2) corrosion test programs confirm these results. These corrosion tests all showed that the wastage process in highly dependent on temperature, pH and local flow velocity.

In addition the NRC/ANL corrosion test program also generated significant new data showing that re-wetting of high temperature molten metaboric acid – a condition previously thought to be relatively non-corrosive - can result in corrosion rates of up to 6 inches per year (Section 6.4.2).

These tests show that under the appropriate conditions, metal removal at high rates will occur. For impingement or flow-assisted corrosion (FAC) this can result in a highly localized penetration rate at low flow and high velocity, and a lower penetration rate but higher volumetric metal removal rate at higher leak flows. Superimposed on these flow assisted corrosion and metal removal mechanisms are the aggressive corrosion rates obtainable in both high temperature molten metaboric acid cooled to 300-340°F by the presence of moisture, and in concentrated aqueous boric acid at lower temperatures in the 200 to 230°F range. (see summary in Section 9.2).

The CFD modeling we have performed and reported in Section 9 support the conclusion that all of these aggressive metal removal processes can occur. In addition, metal removal by the purely mechanical action of the high velocity expanding fluid stream at the crack exit – known as water jet cutting (WJC) and Abrasive Water Jet (AWJ) cutting - provide additional mechanisms for significant material removal at a very rapid rate. (see Appendix E).

The following chronology summarizes the important features of the crack and wastage cavity development at Nozzle 3 at key points in time from late 1998 through to February 2002.

10.2 Cavity Development at Nozzles 3

In order to reach conclusions about the sequence of events that lead to the rapid development of the wastage cavity near Nozzle 3, we have used and taken into account the following:

- The CGR for crack growth in the nozzle above the weld that we developed in Section 8.5.1;
- The weld CGR of 0.7 to 1.0 inches/year that we also developed in section 8.5.1;
- The correlations between leak rate and "effective crack length for leakage" that we developed in Section 9.4 for the nozzle axial cracks and the radial/axial J-groove weld crack;
- The CFD modeling results for Cases 1 through 5 that we developed in Sections 9.5, 9.6 and 9.7;
- The corrosion test data that we described and summarized in Sections 6.3, 6.4 and 9.2;
- The history of RCS unidentified leakage as measured by the RCS inventory balance test and radiation monitoring that we described in Section 7.2;
- The review of plant outage information and CRDM flange leakage that we described in Section 7.3.

10.2.1 12 RFO: Nozzle 3 Crack is Leaking at a Low Rate and a Minor Wastage Cavity Begins to Form at Nozzle 3

- The Nozzle 3 CRDM axial Crack 1 extends to around 0.5 inches above the J-groove weld. The estimated leak rate from this axial nozzle crack is approximately 0.0004 gpm (210 gal/year). This is only 5% of the leak rate estimated for all seven cracks combined at Nozzle 2 in February 2002.

- The metal removal processes likely acting at this time to promote sub-surface cavity growth downward towards the crack were high velocity/low flow mechanical erosion from the fluid exiting the crack and flowing up the annulus. While conditions conducive to the formation of molten metaboric acid existed in the cavity, the low leak flow rapidly dries out and so there is no moisture present to promote boric acid corrosion.

- The maximum boric acid accumulation due to this small leak rate in the last four months of the fuel cycle from December 1999 to April 2000 would have been no more than 1 cubic inch (0.05 lb), even assuming all of the leaking boric acid collected on the RPV head and was not ejected above the mirror insulation and out into the containment building.

- The minute amount of boric acid would have been totally obscured by the boric acid accumulation from five leaking CRDM flanges above the RPV head, one of which was the CRDM Nozzle 3 flange. Complete cleaning of the boric acid accumulation from the RPV head at this time would also have removed the very small amount of boric acid that originated from the CRDM nozzle crack.

- A minor and insignificant sub-surface wastage volume at Nozzle 3 is likely present at this time, but due to the much lower leak rate, this would have been much smaller in axial and radial penetration, annular gap, and total wastage extent than that found at Nozzle 2 at 13RFO. This size of wastage cavity would not have been detectable by any visual or available NDE technique.

- Annulus enlargement at the RPV head surface may have been present, but this would also likely have been much less than that observed at

Nozzle 2 at 13RFO in 2002. Annulus enlargement, if present, would not have been detectable with “through-the-mouse-hole” video inspection techniques, even if the RPV head had been completely cleaned of boric acid at 12 RFO.

10.2.2 October- November 2001 - Weld Crack Uncovers, Leak Rate Dramatically Increases, Cavity Growth Accelerates, and Significant Damage to the RPV Head Occurs

- By October 2001, the leak rate and the cavity size have increased to a critical point after which rapid RPV head metal removal occurs.

- The upward growing Nozzle 3 CRDM axial crack is predicted to be approximately 1.1 inches above the J-groove weld, and extends well into the bottom of the rapidly downward growing wastage cavity. The leak rate at this time is estimated to be 0.02 gpm (10,500 gals/year). This leak rate has increased by a factor of 500 since 12 RFO (May 2000).

- The rate of metal removal at the very bottom of the cavity increases further due to direct impingement of the jet from the crack on the cavity wall, and abrasive water jet cutting is likely due to the extremely high velocities and entrainment of boric acid and corrosion product particles. The removal of the final one-inch of steel remaining above the stainless steel cladding due to these accelerated processes likely occurs in a very short period of time, possibly just a few weeks. In addition, the cavity starts to become undercut due to the more rapid metal removal at the bottom where the crack is located.

- Also by October 2001, in addition to the accelerated corrosion due to wetted molten metaboric acid at the bottom of the wastage cavity, moisture persists all the way through the wastage cavity to the upper RPV head surface. Wastage corrosion due to re-wetting of the molten metaboric acid accumulation on the RPV head begins to cause “top down” corrosion of the head in the region of CRDM Nozzle 3.

- The wide, pre-existing crack in the weld of 0.7 inches in length uncovers and the remaining steel above the weld is quickly removed by the continued jet impingement and abrasive water jet cutting effects of the high fluid velocities, as well as continued corrosion due to wetted molten metaboric acid.

- The total leak rate increases rapidly from the previous 0.02 gpm (10,500 gal/year) to approximately 0.16 gpm (84,000 gal/year) when the weld crack is completely uncovered.

- The rapid increase in leak flow predicted in the October-November time frame as the weld crack uncovered is supported by the plant data. The unidentified leak rate shows an increase of around 0.15 gpm, and both the noble gas and iodine radiation monitors likewise show responses indicative of an increased flow of reactor coolant in the containment building atmosphere.

- This leak flow is now high enough that the fluid stream still contains significant moisture all the way to the top of the wastage cavity and to the underside of the boric acid deposit on the RPV head, which is mostly molten metaboric at the prevailing 550 °F temperature. Wetting of the underside of this deposit over a wider area by the leak flow causes wastage both of the upper portion of the cavity and of the upper RPV head steel around the cavity, leading to the smooth wastage appearance evidenced by the photographs and the dental mold of the cavity.

- The significant increase in the rate of growth of the wastage cavity in this time period is due to the following metal removal processes:

- – Abrasive water jet cutting due to entrained boric acid and corrosion product particles due to the extremely high velocities once the crack and wastage cavity intersect
- – Mechanical erosion by direct jet impingement of the high velocity boric acid liquid stream once the crack and wastage cavity intersect.
- – Accelerated corrosion due to wetted molten metaboric acid.
- – Flow Assisted Corrosion (FAC).

- The wastage cavity grows rapidly as a result of these processes after the weld crack uncovers, causing significant damage to the RPV head in a relatively short period of time, a matter of a few weeks.

- As the cavity grows to its final observed size in March 2002, abrasive cutting slows significantly as the wastage cavity grows and the wastage cavity size becomes too large for efficient material removal by AWJ processes. Fluid velocity at the cavity wall is also significantly reduced due to the increased distance from crack.

- Cavity wastage continues at a significant rate due to flow-assisted corrosion at the bottom of the cavity and wetted molten metaboric acid both throughout the wastage cavity, and “top down” corrosion on the RPV head surface around the cavity continues at a significant rate due the moisture from the crack leak flow.

10.3 Postscript

In a risk assessment of the Davis-Besse event performed in December 2002, the NRC staff reached a similar conclusion. After citing the FENOC root cause report conclusion that the wastage cavity at CRDM Nozzle 3 grew at an average rate of 2 inches/year over the 4-year period of the last two operating cycles, with a maximum corrosion rate near the end of about 4.0 inches/year, the NRC report goes on to discuss the EPRI reported tests of aqueous and molten boric acid corrosion,[a] the various containment indicators of boric acid leakage, and the physical shape of the wastage cavity. The NRC report then concludes, much as we have, that:[2]

> "Therefore, it seems prudent to consider the possibility that the last stages of cavity growth on the Davis-Besse RPV head may have experienced corrosion rates on the order of 7-inches/year. At that rate, the football-shaped portion of the cavity could have begun developing in the latter half of the last operating cycle and reached its observed size by February 2002, when the cavity was discovered.
>
> An interesting coincidence is that there was an abrupt decrease in the necessary rate for CAC cleaning in May of 2001, suggesting that something about the leakage path had changed at that time. The change may have been only in the path past the insulation that the airborne particles followed to reach the containment atmosphere, or it may signify that the leakage had been directed into the pool in the cavity at that time, starting the formation of the football-shaped portion. The containment radiation monitors showed continuing increases in the RCS leak rate until about December 2001."

The large wastage cavity formed in the Davis-Besse RPV head at CRDM Nozzle 3 remains the only event of its kind ever experienced at any PWR. According to EPRI MRP-110, no significant wastage of the RPV head has been reported at any other US or non-US PWR as a result of cracked and leaking CRDM cracks per MRP-110.

The Davis-Besse RPV head wastage event was therefore not the result of ordinary "wear and tear". It was an unanticipated, unforeseeable, and extraordinary "event of the moment" that was brought about by a unique combination of a large, rapidly growing crack in CRDM Nozzle 3, leakage from that crack at a rate and at a location that caused a

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[a] The NRC report written in December 2002, noted that "there are no physical test results available for a situation like the postulated pool of molten orthoboric acid hydrated by a low rate of water leakage into the pool." The results recently reported by the NRC/ANL test program were designed to at least partially fill this knowledge gap, and showed corrosion rates for this condition of up to 6 inches per year. (Section 6.4.2)

unique thermal hydraulic environment to develop in the nozzle annulus, that in turn caused the wastage cavity to develop at not just an unusual, but at an unprecedented rate.

Figure 10.1 Top view of wastage cavity.

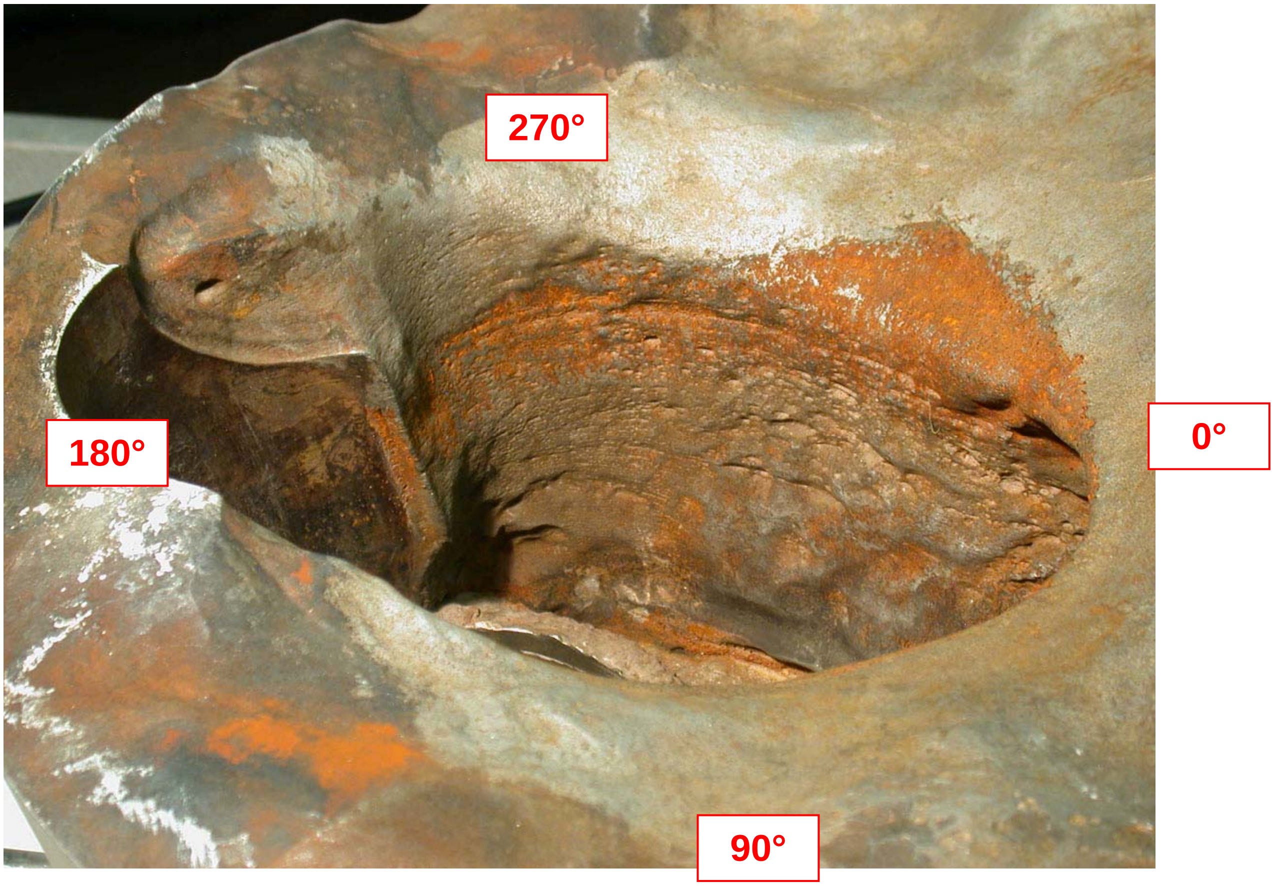


Figure 10.2 View of cavity looking toward 270°

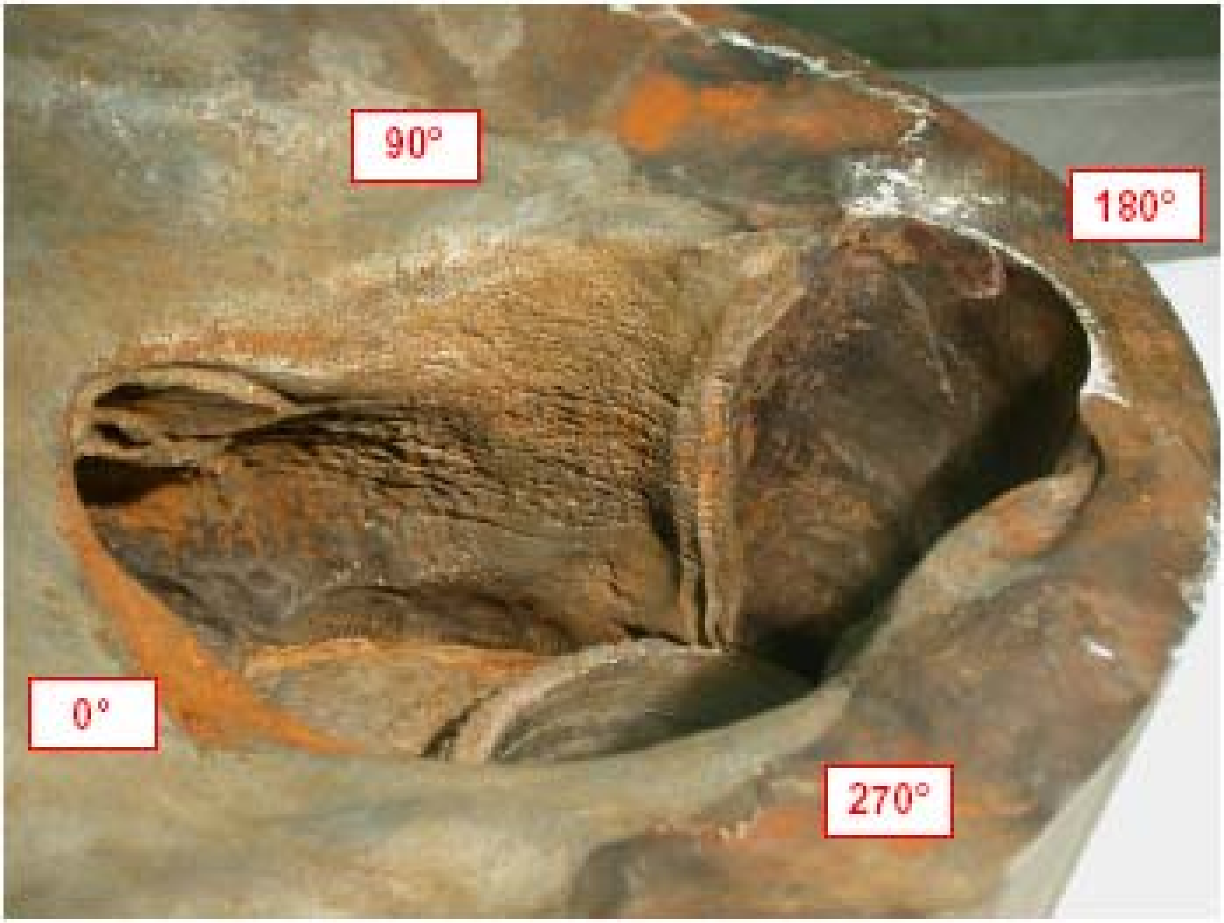
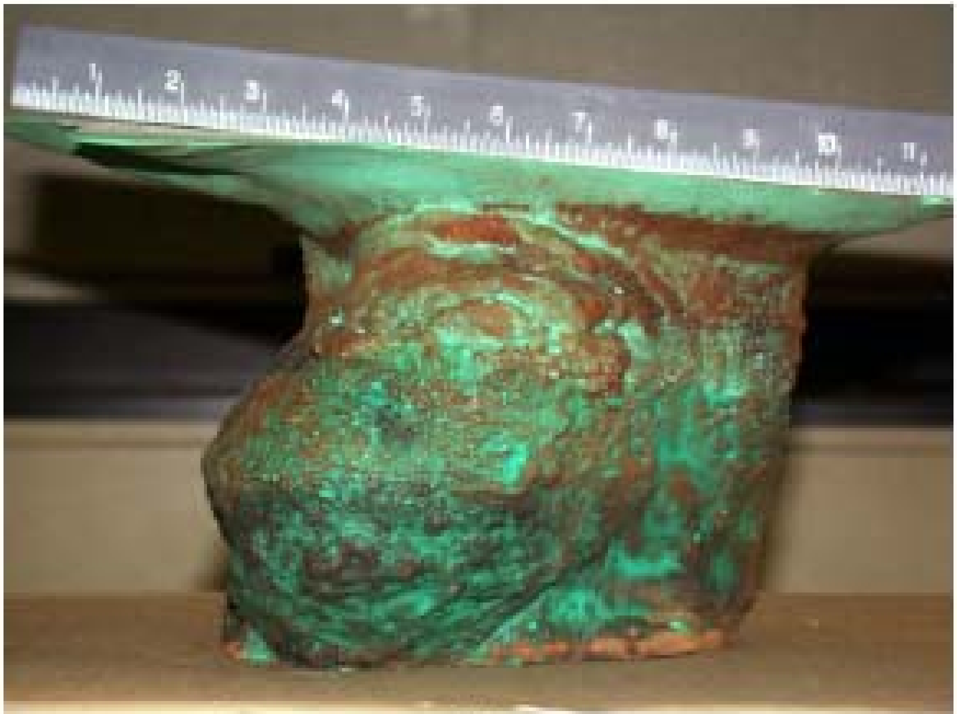


Figure 10.3 View of cavity looking toward 90°

Looking toward 90° ~0.7X

Looking toward 270° ~0.5X

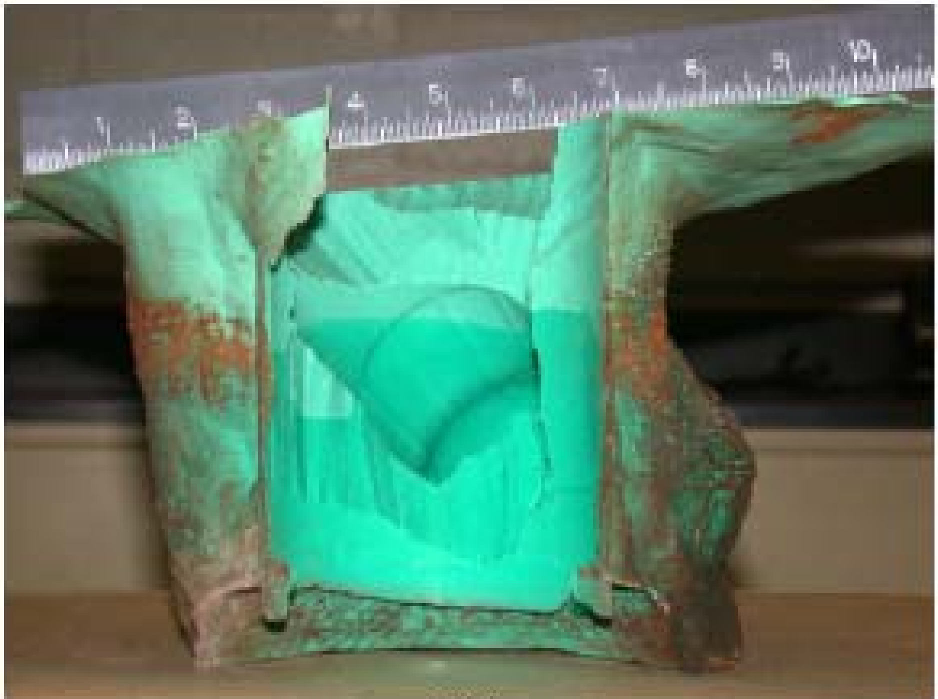
Figure 10.4 Low magnification photographs of cavity sidewalls



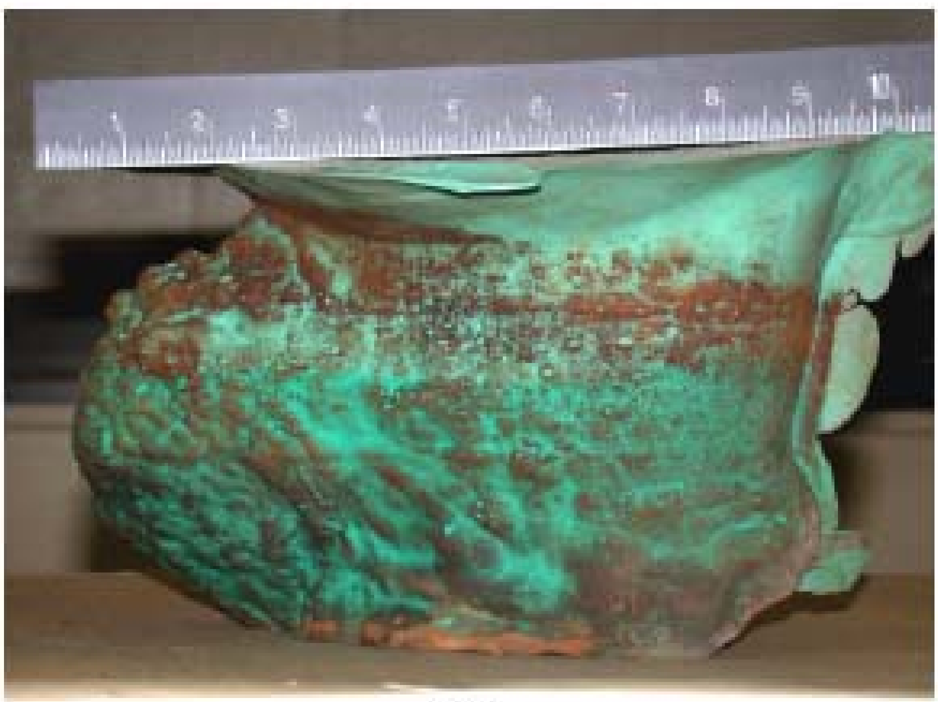
0°

90°

Figure 10.5(a) Photographs of cavity dental mold



180°



270°

Figure 10.5(b) Photographs of cavity dental mold

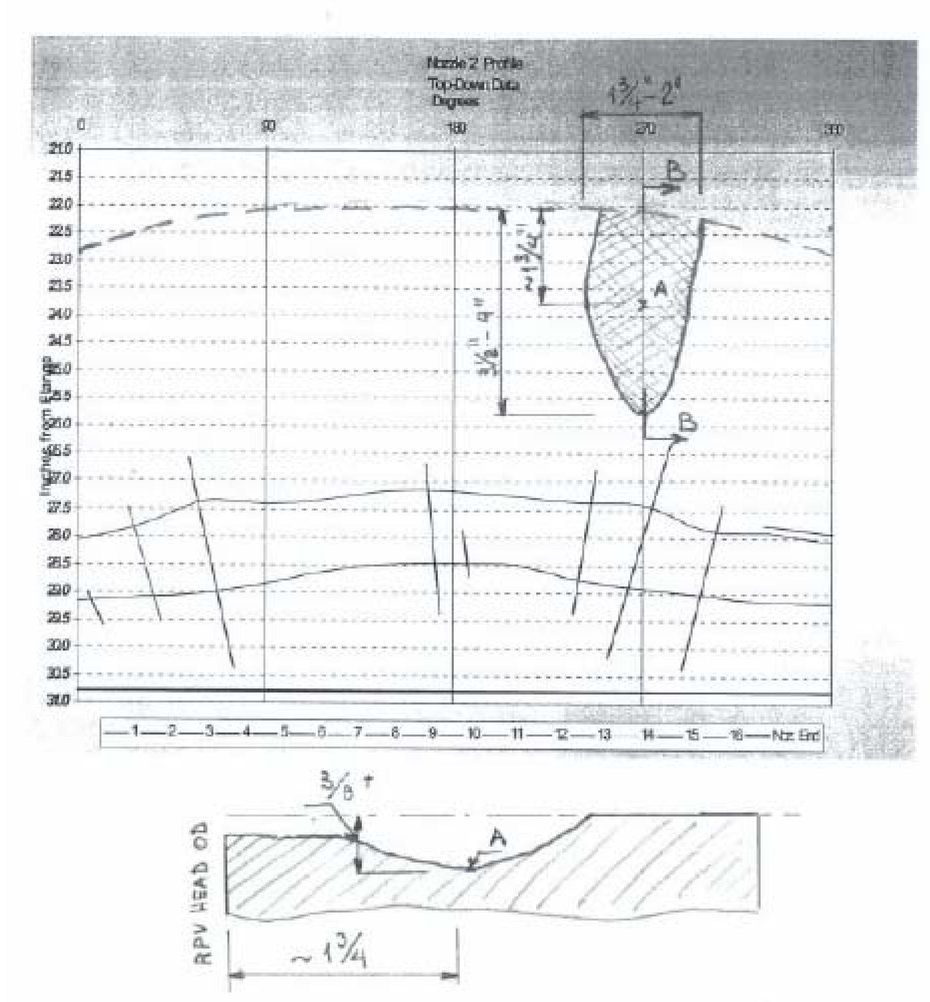


Figure 10-6 Wastage Cavity at CRDM Nozzle 2

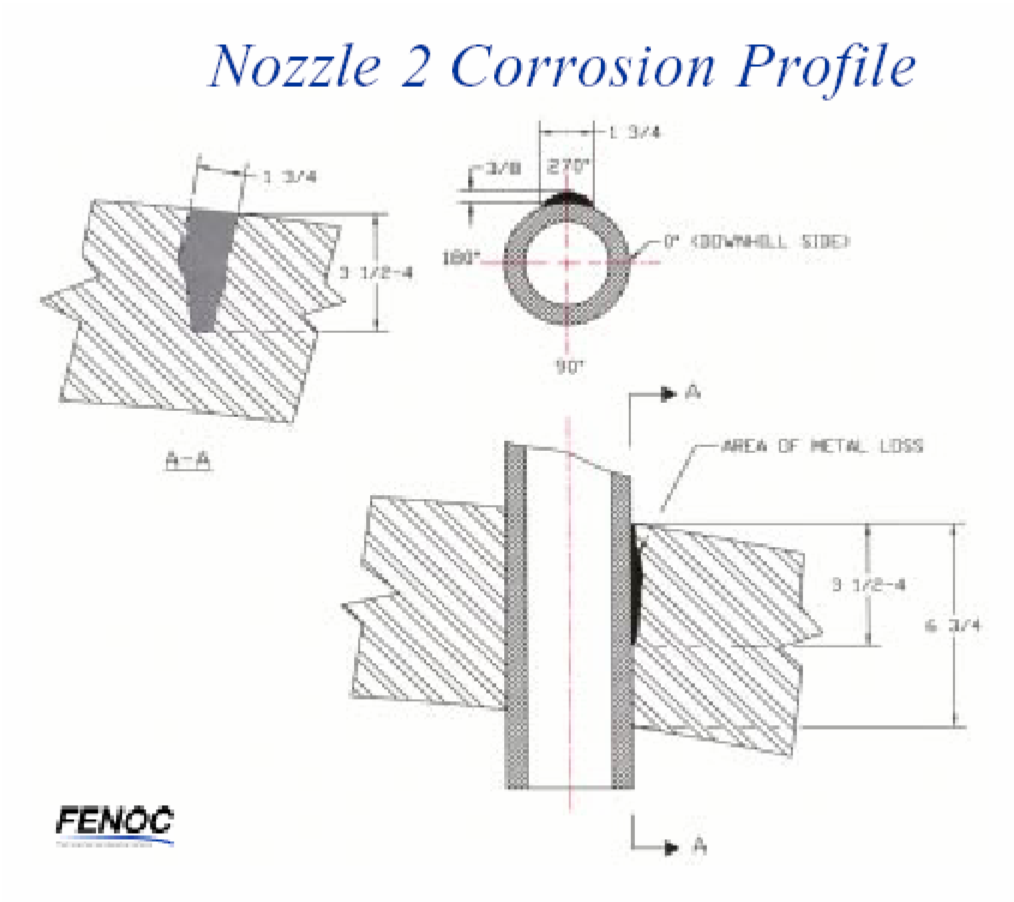


Figure 10-7 Wastage Cavity at CRDM Nozzle 2

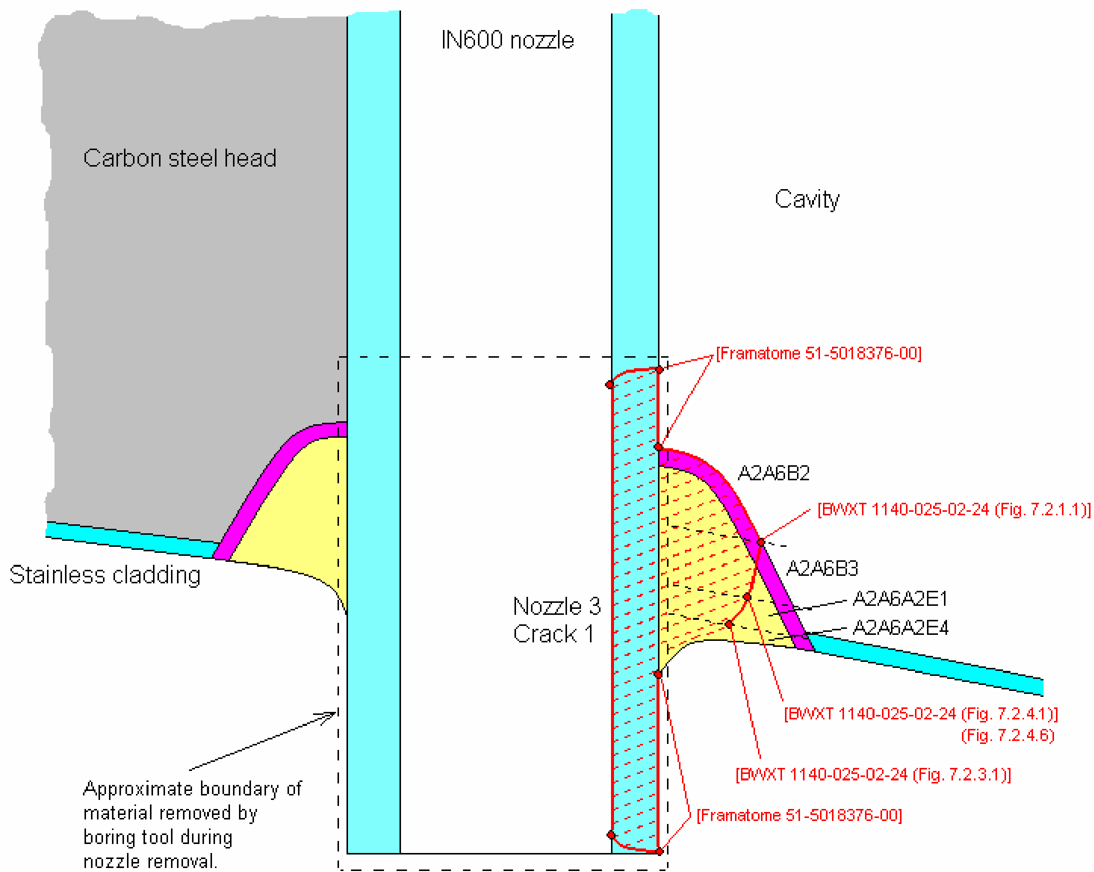


Figure 10.8 Schematic of final size and shape of Crack 1 in Davis-Besse CRDM Nozzle 3 (from Section 8, Figure 8-10)

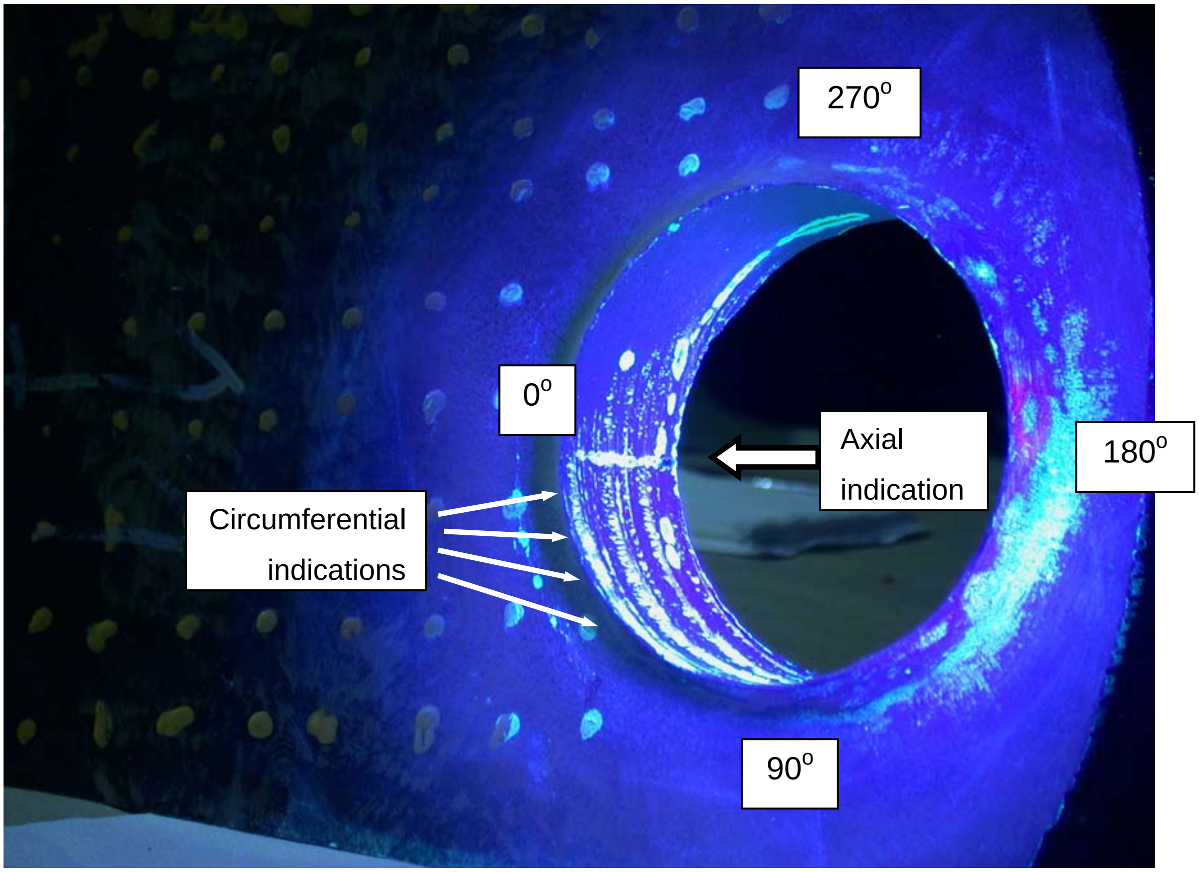
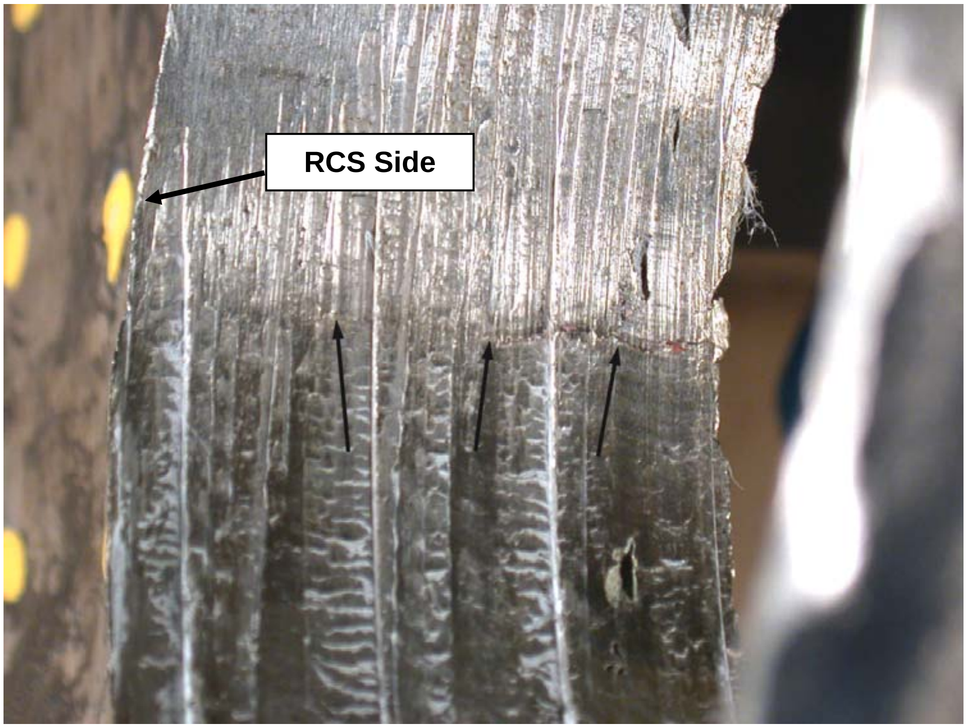
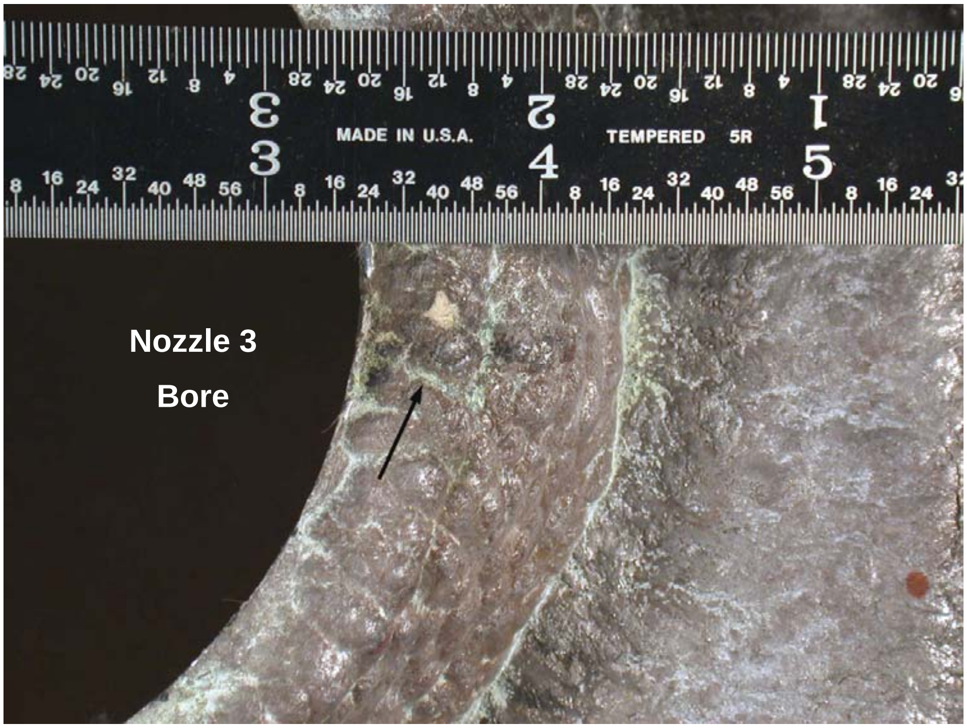


Figure 10.9 PT results for nozzle 3 J-groove weld bore and cladding underside. The J-groove weld contained an axial indication near 10° on the bore ID and circumferential indications on the RCS side from ~20° to ~45°.



Looking at J-groove weld bore near 10°. ~1.2X

Figure 10.10 Photograph showing the remaining portion of the axial crack near 10° in the CRDM Nozzle 3 J-groove weld. This is the portion remaining after the machining was completed for nozzle repair.



Top view of J-groove weld crack near 10°. ~1.4X

Figure 10.11 Photograph showing axial crack in CRDM nozzle 3 J-groove weld near 10°.

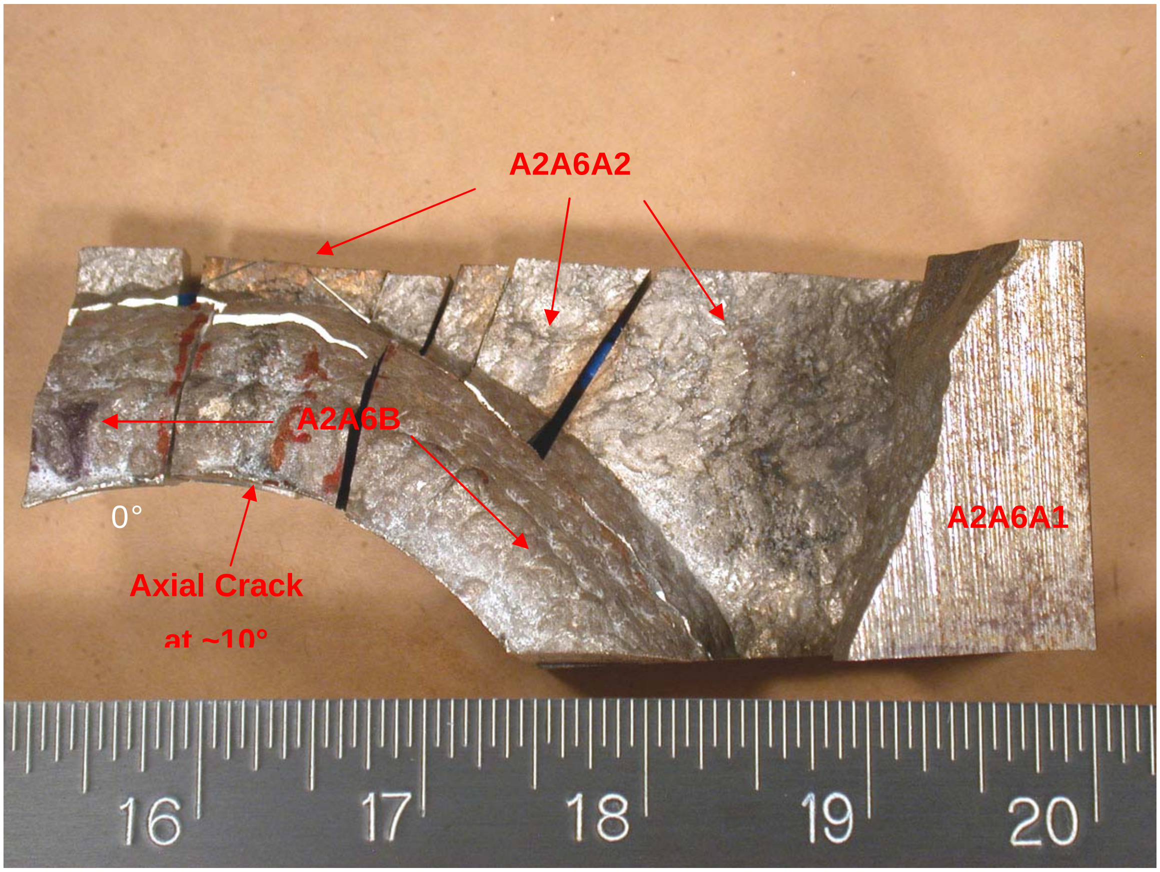
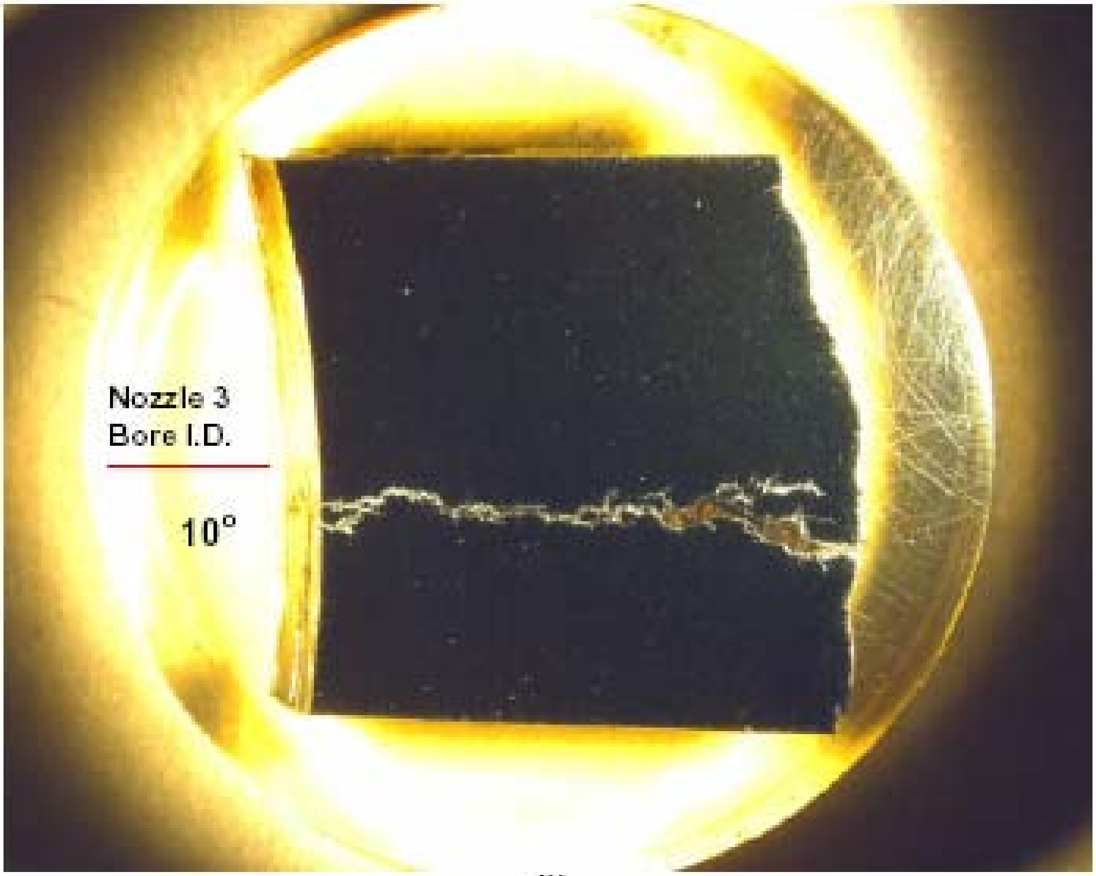
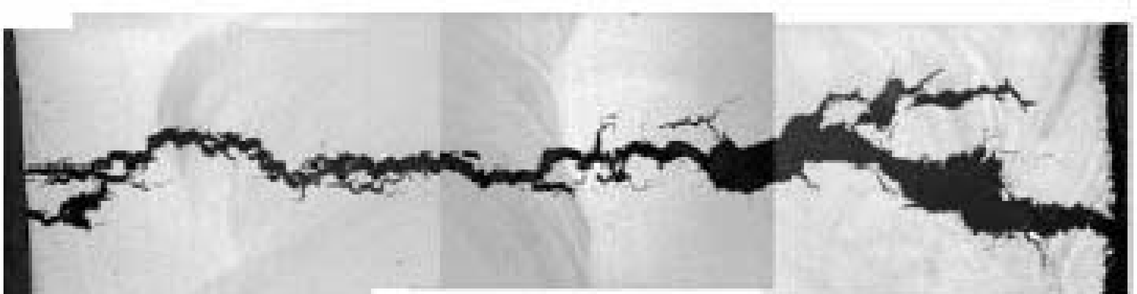


Figure 10.12 Piece A2A6 was first sectioned into Pieces A2A6A and A2A6B. Piece A2A6A was further sectioned into Pieces A2A6A1 and A2A6A2. Both cuts were made on the same plane, parallel to the paper. The first cut line is partially visible; Piece A2A6B is the upper portion of the weld. The second cut line between Pieces A2A6A1 and A2A6A2 is obscured by Piece A2A6A1

Figure 10.13 Piece A2A6B after sectioning. The bottom surface of A2A6B2 was mounted. The axial crack in A2A6B3 was opened up for SEM.



4X



Etched 8X

Figure 10.14 Macro photograph of metallographic mount sample A2A6B2 (see Figures 5.4 and 5.5 for the sample orientation). The axial cracking at ~10^{o} is through the J-groove weld, in contrast to the cracking near 180^{o}, which was partially through the weld. A slightly higher magnification micrograph is also provided

10.4 References

1. “Final Report: Examination of the Reactor Vessel (RV) Head Degradation at Davis-Besse,” Report No. 1140-025-02-24, BWXT Services, Inc., June 2003.

2. “Response to Request for Technical Assistance – Risk Assessment of Davis-Besse Reactor Head Degradation”, Davis-Besse SERP Attachment 2, December 6, 2002, Attachment A at pages 8, 9.